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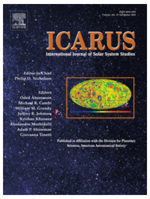

The New Horizons and Hubble Space Telescope search for rings, dust, and debris in the Pluto-Charon system

Tod R. Lauer[a,1,*], Henry B. Throop[b], Mark R. Showalter[c], Harold A. Weaver[d], S. Alan Stern[e], John R. Spencer[e], Marc W. Buie[e], Douglas P. Hamilton[f], Simon B. Porter[e], Anne J. Verbiscer[g], Leslie A. Young[e], Cathy B. Olkin[e], Kimberly Ennico[h], New Horizons Science Team[a,b,c,d,e,f,g,h]

[a] *National Optical Astronomy Observatory, P.O. Box 26732, Tucson, AZ 85726, USA*
[b] *Planetary Science Institute, 1700 E Fort Lowell Rd. #106, Tucson, AZ 85719, USA*
[c] *SETI Institute, Mountain View, CA 94043, USA*
[d] *The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723-6099, USA*
[e] *Department of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302, USA*
[f] *Astronomy Department, University of Maryland, College Park, MD 20742, USA*
[g] *Department of Astronomy, University of Virginia, Charlottesville, VA 22904, USA*
[h] *NASA Ames Research Center, Moffett Field, CA 94035, USA*

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ABSTRACT

We conducted an extensive search for dust or debris rings in the Pluto-Charon system before, during, and after the New Horizons encounter in July 2015. Methodologies included attempting to detect features by back-scattered light during the approach to Pluto (phase angle $\alpha \sim 15^\circ$), *in situ* detection of impacting particles, a search for stellar occultations near the time of closest approach, and by forward-scattered light imaging during departure ($\alpha \sim 165^\circ$). An extensive search using the Hubble Space Telescope (HST) prior to the encounter also contributed to the final ring limits. No rings, debris, or dust features were observed, but our new detection limits provide a substantially improved picture of the environment throughout the Pluto-Charon system. Searches for rings in back-scattered light covered the range 35,000–250,000 km from the system barycenter, a zone that starts interior to the orbit of Styx, the innermost minor satellite, and extends out to four times the orbital radius of Hydra, the outermost known satellite. We obtained our firmest limits using data from the New Horizons LORRI camera in the inner half of this region. Our limits on the normal I/F of an unseen ring depends on the radial scale of the rings: 2×10^{-8} (3σ) for 1500 km wide rings, 1×10^{-8} for 6000 km rings, and 7×10^{-9} for 12,000 km rings. Beyond $\sim 100,000$ km from Pluto, HST observations limit normal I/F to $\sim 8 \times 10^{-8}$. Searches for dust features from forward-scattered light extended from the surface of Pluto to the Pluto-Charon Hill sphere ($r_{\rm Hill} = 6.4 \times 10^6$ km). No evidence for rings or dust clouds was detected to normal I/F limits of $\sim 8.9 \times 10^{-7}$ on $\sim 10^4$ km scales. Four stellar occultation observations also probed the space interior to Hydra, but again no dust or debris was detected. The Student Dust Counter detected one particle impact 3.6×10^6 km from Pluto, but this is consistent with the interplanetary space environment established during the cruise of New Horizons. Elsewhere in the solar system, small moons commonly share their orbits with faint dust rings. Our results support recent dynamical studies suggesting that small grains are quickly lost from the Pluto-Charon system due to solar radiation pressure, whereas larger particles are orbitally unstable due to ongoing perturbations by the known moons.

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* Corresponding author.
E-mail address: lauer@noao.edu (T.R. Lauer).

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1. Searching for rings and dust around Pluto

1.1. Could Pluto have rings?

It is likely that Pluto had rings[2] at various times in its history, although their existence may have been fleeting. The standard model for the formation of both Charon and the four minor satellites of Pluto is that they were created in a collision between Pluto and another large KBO (Mc Kinnon, 1989; Canup, 2005; Stern et al., 2006), which would have created an extensive debris disk. Dynamical interactions would have quickly cleared most of the larger debris, and solar radiation pressure sweeps away much of the fine dust (Pires dos Santos et al., 2013); however, it is plausible that remnants of this initial event could have persisted at large radii into the present (Kenyon and Bromley, 2014). The recent discovery of rings around the Centaur-object (10199) Chariklo (Braga-Ribas et al., 2014), and possibly Chiron (2060) (Ruprecht et al., 2015; Ortiz et al., 2015), vividly demonstrates that small solar system bodies may indeed possess rings in their own right (also see the discussion in Sicardy et al., 2016).

Apart from "fossil" rings left over from the initial creation of the satellite system, we might expect to find diffuse dust rings arising from ongoing impact erosion of the minor satellites. Durda and Stern (2000) argued that the frequency of collisions within the Kuiper Belt is high enough to cause significant erosion of all small KBOs over the age of the solar system. In the specific context of Pluto, Stern et al. (2006), Steffl and Stern (2007), Stern (2009), and Poppe and Horányi (2011) predicted that impact gardening of the minor satellites Hydra and Nix (and by implication Kerberos and Styx, which were discovered later) could inject fine debris or dust into the environment around Pluto and Charon, leading to transitory or long-lived rings. (Escape velocities are too high for this mechanism to generate rings directly from Pluto or Charon.)

On theoretical grounds, Stern et al. (2006) estimated that a ring generated from steady-state erosion of Hydra and Nix would have optical depth $\tau = 5 \times 10^{-6}$. Poppe and Horányi (2011) argued for a shorter particle lifetime, yielding $\tau = 10^{-7}$. Given the dynamic complexity of Pluto and Charon plus the four minor satellites, a key theoretical problem is identifying orbits that can host stable rings. Poppe and Horányi (2011) and Pires dos Santos et al. (2013) showed, for example, that long-lived rings could exist between the orbits of Nix and Hydra, as well as at co-orbital locations in the orbits of the four minor satellites. However, the subsequent discovery of Kerberos orbiting between these two moons partially invalidated their conclusions (Porter and Stern, 2015).

On the other hand, Pires dos Santos et al. (2013) argued that solar radiation pressure is sufficient, even at the distance of Pluto, to clear small particles from the system, given Pluto's overall shallow gravity well. They predicted that the optical depth of any long-lived dust ring would be no more than 4×10^{-11}, well below any feasible detection limits. This result holds despite the substantial rates of impact gardening estimated by Durda and Stern (2000) (a significantly lower rate may be implied by the crater counts measured by Singer et al., 2017). Furthermore, simulations by Youdin et al. (2012) and Showalter and Hamilton (2015) show the system to be chaotic, raising questions about the long-term stability of the small moons themselves, irrespective of any embedded rings. Interior to the orbit of Charon, long-lived rings are unlikely to exist due to the drag induced by Pluto's extended atmosphere (Porter and Grundy, 2015).

Because this debate has been inconclusive, it remained an open question whether Pluto might have faint rings above the sensitivity threshold of the New Horizons (NH) cameras. Beyond the scientific interest in such rings, their possible existence also raised concerns about a potential hazard to the spacecraft during its passage through the system.

1.2. Previous searches for Plutonian rings

A few attempts were made to detect rings in advance of the NH encounter. Steffl and Stern (2007) used high-resolution images of Pluto and Charon taken with the ACS/HRC instrument on board the Hubble Space Telescope (HST) to derive upper limits for the visibility of any rings in back-scattered, visual-band sunlight. Their detection limits were controlled by the scattered-light background and thus varied with projected distance from Pluto. At the orbit of Hydra, they limited the rings' normal I/F to $\sim 2.5 \times 10^{-7}$. That limit approximately doubles at the inner limit of orbital stability, which is $\sim 42,000$ km.

Like Steffl and Stern (2007), we measure intensity I by the dimensionless ratio I/F, where πF is the incoming solar optical flux density at Pluto. With this definition, I/F would equal unity for a perfectly diffusing "Lambert" surface when illuminated and viewed normal to the sunlight. For a body with geometric albedo A viewed at phase angle α, its surface reflectivity would be $I/F = A\ P(\alpha)/P(0)$, where P is the phase function.

Above, we quote values of "normal" $I/F \equiv \mu I/F$, which is a more useful quantity for describing optically thin rings. Here the observed I/F is scaled by a factor $\mu = \cos(e)$, where e is the emission angle measured from the ring plane normal. The μ factor compensates for the apparent brightening of an optically thin ring when viewed closer to the ring plane, so normal I/F describes the reflectivity that would be detected if $e = 0$. Normal I/F and optical depth τ are related via

$$\mu I/F = \tau A \times P(\alpha)/P(0). \tag{1}$$

For Steffl and Stern (2007), A was extremely uncertain, plausibly ranging from 0.04 (for bodies resembling dark KBOs) to ~ 0.38, which is the geometric albedo of Charon. Today, we know that any ring dust is most likely to have albedos comparable to that of the nearby moons, for which $A = 0.5–0.9$ (Weaver et al., 2016), higher than previously suspected. Nevertheless, because I/F is the measured quantity in image analysis, we discuss most of our findings below in terms of normal I/F. We revisit the optical depth values in the final discussion and summary section.

Other techniques have also been applied to searches for rings of Pluto. Boissel et al. (2014) and Throop et al. (2015) separately used stellar occultations to search for rings. Occultations could potentially detect compact or narrow rings with widths well below the HST resolution limit. Unlike image measurements, occultations obtain τ directly; however, these experiments did not provide better limits for diffuse rings. Lastly, Marton et al. (2015) used far-IR images (70 µm) from the Herschel Telescope to look directly for thermal emission from dust around Pluto and Charon, but again found limits broadly compatible with the HST results of Steffl and Stern (2007).

1.3. Overview

The initial summary of science results from the NH encounter noted that no dust features or rings with normal $I/F > 10^{-7}$ were detected based on a preliminary analysis of the imaging searches conducted by the spacecraft during its approach (Stern et al., 2015). We have three goals for this dedicated ring-search paper that go beyond this initial result. The first is to summarize the results of a preliminary ring search performed using HST during

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[2] For brevity, we generally describe the search for all such features as a search for "rings" throughout the paper, even though the observations and analysis are sensitive to diffuse or extended debris or dust features as well.